Refrigerative Stereolithography for Support-Free and Accurate Fabrication

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ABSTRACT

A "refrigerative stereolithography" process is presented in this paper. In this process, a photopolymer resin for one building layer is supplied in a liquid state and cooled to become gel state before photopolymerization by laser. After repeating this process for all layers, a fabricated object is obtained by heating, melting and removing the non-photopolymerized resin from around the object. Since the object is fabricated in gel state resin, support structures are unnecessary and distortion by photopolymerization is reduced. A method of restraining surplus growth, which is caused by the overcuring of the bottom surface of solidified parts, is also proposed. The effectiveness of the method is confirmed by fabrication experiments using a prototype machine.

INTRODUCTION

In conventional stereolithography, support shapes are necessary for accurate fabrication. The design of the support shapes is currently performed automatically by software; however, users must remove them manually after fabrication and this takes much time and effort. Furthermore, it is difficult to fabricate complicated objects that include jointed structures or any other assembled structures, because support shapes, in these cases, are difficult to remove. Support shapes are one of the factors preventing the fabrication of objects with a high degree of freedom. Also, in stereolithography, since a solidified layer must be connected in principle to the previous layer, excessive exposure is needed to solidify the resin layer beyond one layer thickness [1]. Therefore, surplus growth caused by overcuring occurs at the bottom surface of the solidified layers and leads to a dimensional error in the height direction [2]. The objective of this paper is to propose a new stereolithography method referred to as "refrigerative stereolithography" to overcome the problems described above, and to describe the effectiveness and possibility of the method on the basis of fabrication experiments using a prototype machine.

REFRIGERATIVE STEREOLITHOGRAPHY

The refrigerative stereolithography fabrication process is shown in Figure 1. In this process, photopolymer resin is supplied in a liquid state on a platform for one layer thickness and flattened at first (Figure 1(a)), then rapidly cooled to turn to a solid state (Figure 1(b)). The resin surface is selectively exposed using a laser beam to solidify the photopolymer resin (Figure 1(c)), and then the platform is lowered by one layer thickness (Figure 1(d)). After repeating these processes for all layers, a solid block which contains the target object inside is removed from the platform, and by heating, melting and removing the non-photopolymerized resin remaining around the object (Figure 1(e)), the desired product is obtained (Figure 1(f)). During steps (a) through (d) in Figure 1, as the solidified parts cured using a laser beam are completely supported by non-photopolymerized resin, there is no need for supports for these parts. The main advantages of refrigerative stereolithography are as follows.

1. There is no need for support structures during the part building process.
2. The fabrication of the objects with a high degree of freedom such as jointed structures is available.
3. An accurate resin surface is possible because there is no surface tension when the resin is used in the liquid state.
4. Additional mechanical treatments on the resin surface are possible since the resin surface is in a frozen solid state [3].

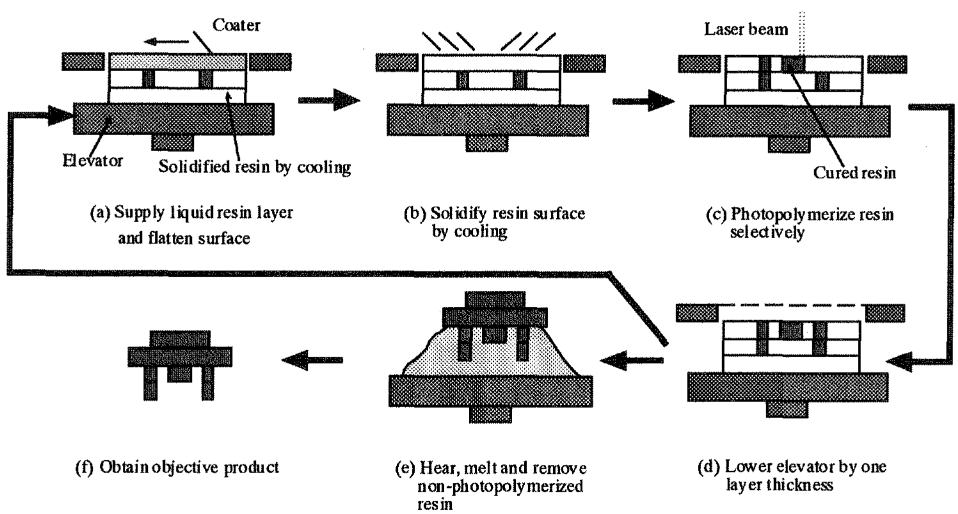


Figure 1: Process of refrigerative stereolithography

RESIN FOR REFRIGERATIVE STEREOLITHOGRAPHY

The photopolymer resin used in the refrigerative stereolithography process is required to be in a liquid state with a low viscosity while it is supplied at a temperature above but as close as possible to room temperature. In addition, it is required to be in a solid state for supporting the cured parts at room temperature. Therefore, we selected a new type of resin that exists in a gel state at room temperature but turns to a sol state at about 80°C. This photopolymer resin, ST1214-LW25, is composed of two ingredients, commercial urethane-acrylate photopolymer resin and sol-gel changeable resin. The resin changes phases, from gel to sol or from sol to gel, very sharply in a narrow temperature range. The gel strength at room temperature is very important for preventing the deformation of cured resin layers. The resin ST1214-LW25 has the gel strength of 600kPa; this is sufficient for restraining the deformation of the solidified parts as supports.

In the refrigerative stereolithography fabrication process, the heated sol-state resin is supplied onto the surface of the cooled gel state resin. Therefore, if the gel-state resin surface in the previous layer is melted by the heat from the heated sol-state resin, cured parts may move while recoating or deform due to the heat. To confirm how the temperature of the resin surface changes during recoating, we carried out some experiments. In these experiments, as shown in Figure 2, two small thermocouples were placed on the resin surface in the building area separated by 2cm, and the temperatures at the position of these thermocouples were measured. The resin was manually supplied by a metal blade which was heated to 110℃, and the resin surface was cooled to room temperature by a fan. Table 1 lists the experimental conditions. The results are illustrated in Figure 3. From the results, it is clear that the temperatures of the two points on the resin surface drop slightly after the resin is supplied, and that about 20 seconds is needed for the supplied resin to cool down to room temperature. The highest temperature of the thermocouple (a) is about 60℃, which is below the phase change temperature of the resin ST1214-LW25. Therefore, during the process of resin supply there is no possibility of cured part movement or deformation.

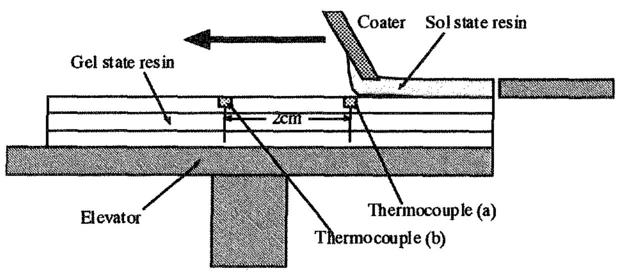


Figure 2: Schematic of experiment for measurement of resin surface temperature while recoating

Table 1: Conditions of experiments for measurement of resin surface temperature

	Data
Recoating speed [cm/sec]	8
Layer thickness [μ m]	100
Blade temperature [°C]	110
Resin temperature [°C]	100
Circumstance temperature [°C]	27

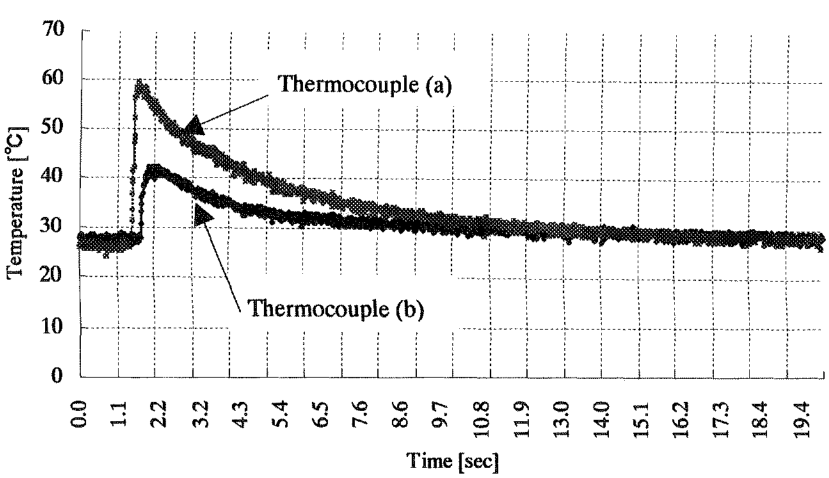
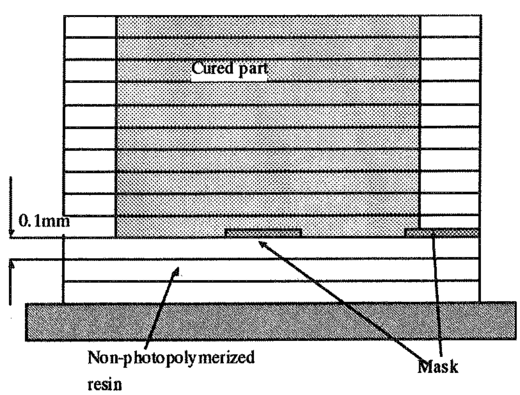


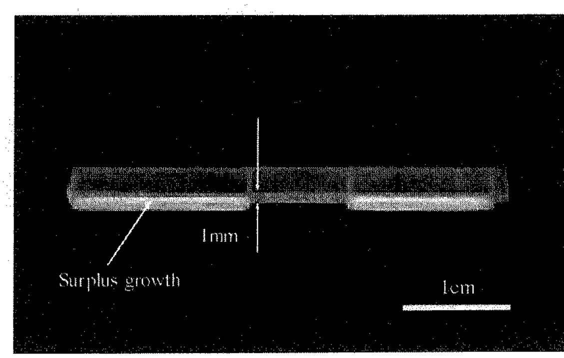
Figure 3: Temperature vs time during recoating process

NEW METHOD FOR RESTRAINING SURPLUS GROWTH

In the stereolithography fabrication process, since a solidified layer must be bonded to the previous layer, excessive laser exposure is needed to solidify the resin beyond one layer thickness. Therefore, surplus growth caused by the overcuring occurs at the bottom surface of the solidified layers and leads to a dimensional error in the height direction. Refrigerative stereolithography makes it possible to fabricate the assemblies in a single process, therefore accurate clearance between each individual component becomes important. To build clearances accurately, we propose a new method of drawing masking layers on the resin surface which intercept surplus laser light. Experiments were carried out to verify the effectiveness of this method. In these experiments, as shown in Figure 4(a), the masking layers were drawn manually with a white pen for masking directly on the resin surface only once at the bottom layer of the desired product. The resin for one layer of thickness of 100μm is supplied and then cured by the laser beam. After repeating this process ten times, the fabricated part shown in Figure 4(b) was obtained. Figure 4(b) shows that there is no surplus growth at the masked regions and the thickness there is just 1mm as measured by a micrometer. Also, the bottom surface at the masked regions is flatter than those of objects produced using conventional stereolithography.



(a) Schematic of masking experiment



(b) Fabricated object

Figure 4: Experiment for surplus growth

PROTOTYPE MACHINE FOR REFRIGERATIVE STEREOLITHOGRAPHY

A prototype machine based on refrigerative stereolithography and the new masking method was designed and produced. In designing the prototype machine, the following elements were examined.

Laser and scanning mechanism

In the prototype machine, a 40mW He-Cd laser(325nm) is used. The laser beam derived from the laser source is reflected by four sets of optical mirrors and then focused on the resin surface by an optical convexo-plane lens which is placed on a carrier equipped with the XY-plotter. The XY-plotter mechanism works to scan the laser beam across the resin surface. The resolutions in the X and Y axes of the XY-plotter are 10μm and 25μm respectively and the iteration accuracy of the two axes is approximately ±100μm. The power of the laser beam focused on the resin surface is controlled by an AOM (audio optical modulation) device, while in conventional machines it is used to shut off the laser beam.

Resin supply unit

The ST1214-LW25 photopolymer resin currently used in our system is stored in a heated resin tank and led to the resin supply unit through a heated pipe. The amount of resin being supplied at any one time is controlled by an electric valve which is attached to the resin supply unit. Since the resin tank is located at a position higher than the resin supply unit, no special pump is required. The resin supply is performed by a coater which is connected to the XY-plotter carrier by a magnet only when the resin is supplied, and detached after the recoating process. Figure 5 schematically shows the process of resin supply. All of the components used for the resin supply are heated to 100°C and maintained at that temperature.

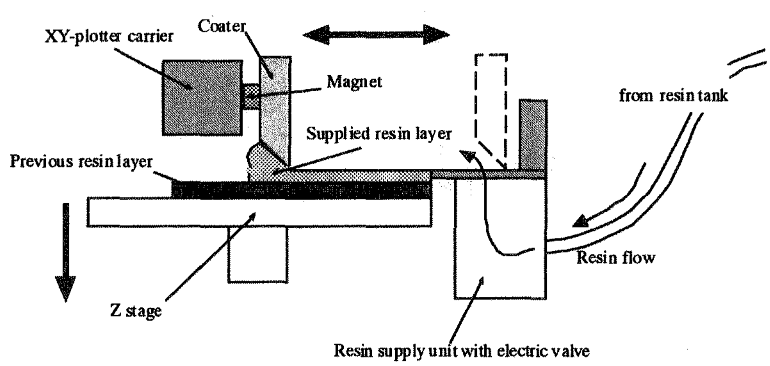


Figure 5: Schematic of resin supply process

MECHANISM FOR DRAWING MASK

The masks for intercepting the surplus light from upper layers are drawn by an inkjet head, which is located below the XY-plotter carrier and moves with it. The inkjet head has a nozzle 40μm in diameter. Ink dots are discharged from the nozzle by the vibration of a metal plate connected to a piezo actuator. The diameter of the ink dot when it drops onto the resin surface is approximately 200μm. Therefore, it is currently impossible to mask areas that are smaller than the ink dot, such as a line of width of 150μm.

SLICE DATA OF PROTOTYPE MACHINE

Slice data of a 3-D object is obtained by the following processes. At first, a solid model of the object is designed in a 3-D CAD system and converted into a STL file. Next, the STL file is loaded into a developed slice software by which the STL file is "sliced" into a series of slice datum for the prototype machine. The slice data is a bitmap format file for each one of the layers, compressed by a run length method. It also consists of information such as the object sizes, the resolution of one dot which is equivalent to the minimum building unit size, and the masking data.

POSTPROCESSING OF FABRICATED OBJECT

After the fabrication, the obtained solid blocks are immersed in toluene solvent in an ultrasonic cleaner to rinse and remove the non-photopolymerized portions. After that, the object is post-cured using a UV lamp and the desired product is obtained.

Figure 6 is a configuration of the experimental prototype machine. The specifications of the prototype machine are listed in Table 2.

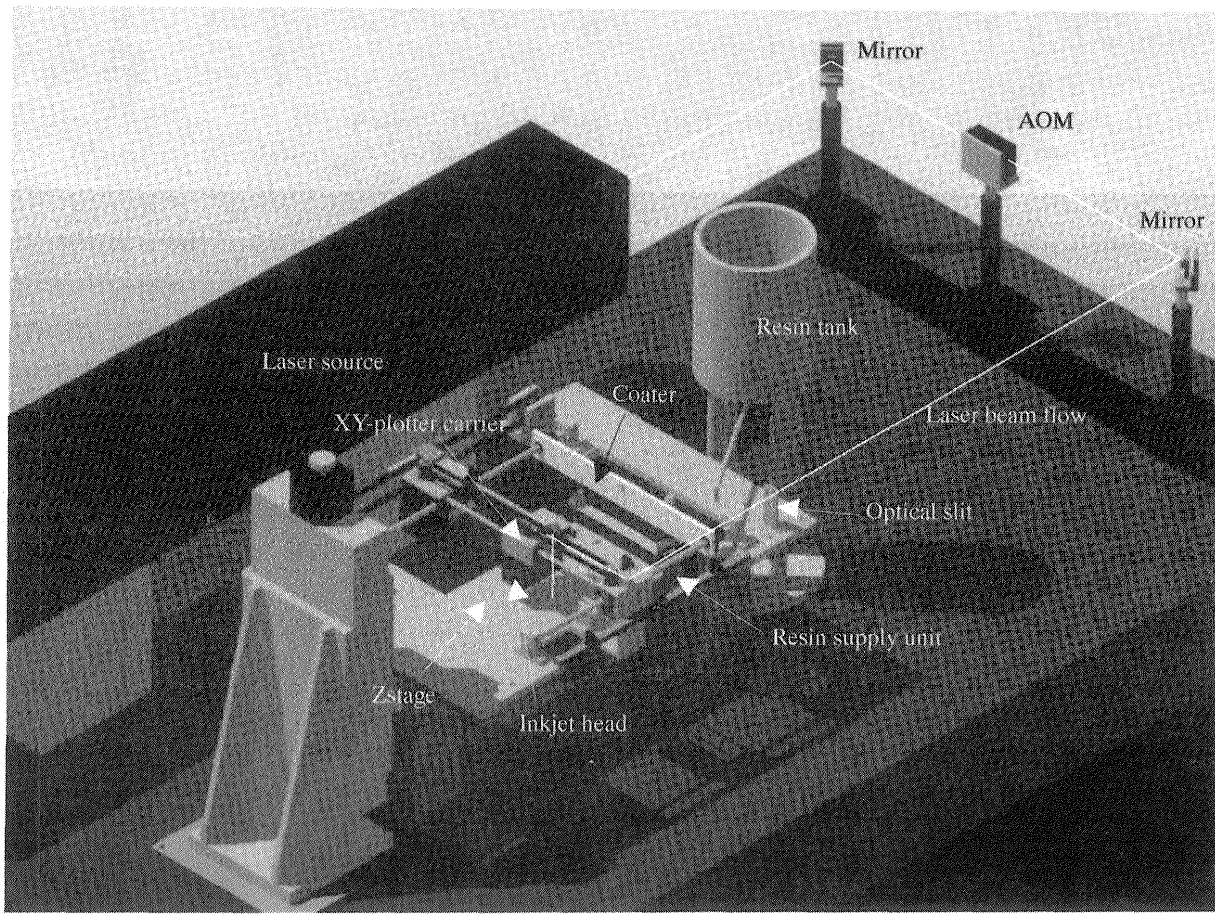


Figure 6: Configuration of designed and produced prototype machine

FABRICATION EXPERIMENT

To confirm the effectiveness of the prototype machine based on refrigerative stereolithography and the masking method, we carried out fabrication experiments. The main objective of these experiments was to attempt to fabricate assemblies which contain small, accurate clearances between individual components. Figure 7 shows a designed sample model which contains two individual components, and the clearances between them are 100μm in the height direction. The plate located in the middle of the object can rotate around the shaft. The clearance between the shaft and the plate is 200μm. The parameters for the fabrication experiment are listed in Table 3.

RESULTS AND DISCUSSION

Photographs of the object fabricated in the experiment above are shown in Figure 8. From these photos, it is verified that the clearances between the two components in the height direction were accurately fabricated and the plate in the middle could be turned smoothly around the shaft. The clearances between the top of the plate and the casing part, and between the bottom of the plate and the casing part are 105μm, and 106μm, respectively. The fabricated object is colored which is due to residual inks from the masking layers. Since commercial pigment colored ink is currently used, there are some problems with the reflection and penetration of light, and also the objects lose their transparency. Each mask is drawn three times at the same place on the resin surface, so as to block the penetration of light. However, this causes another problem in that it increases the mask thickness. To avoid this problem, we plan to use particulate oxidized titanium as the ink, which has excellent transparency and blocking capability of UV light.

Table 2: Specifications of produced prototype machine

Laser	He-Cd, 40mW, 325nm
Laser beam power control	AOM
XY scanning of laser beam	XY-plotter Resolution X 10μm, Y 25μm Iteration accuracy ±100μm Maximum scanning speed 50cm/sec
Z feed of elevator	Z stage with stepping motor Resolution 1μm Iteration accuracy ±10μm
Maximum work size (X,Y,Z)	120, 120, 100 mm
Photopolymer resin	ST1214-LW25
Inkjet head	One nozzle, 40 μm diameter

Table 3: Parameters for fabrication experiment

Photopolymer resin	ST1214-LW25
Resin supply temperature	100 ℃
Layer thickness	100 μm
Laser power	3 mW
Scanning speed	30 mm/sec
Scanning interval	0.1 mm
Object size	9×28×5.2 mm

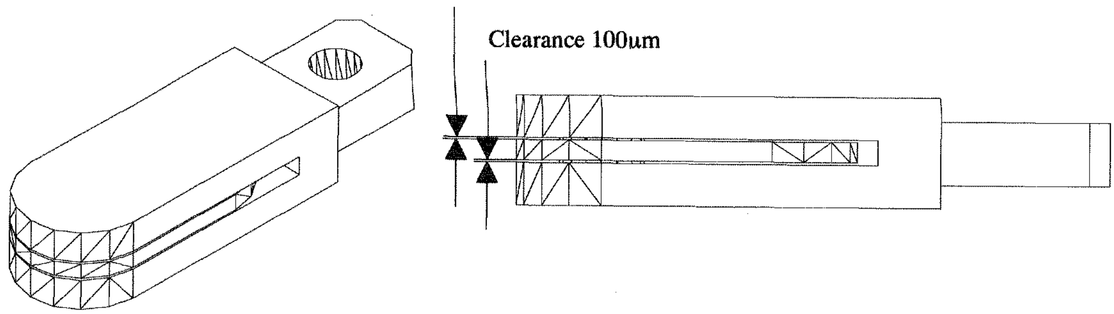


Figure 7: Designed 3D-CAD model

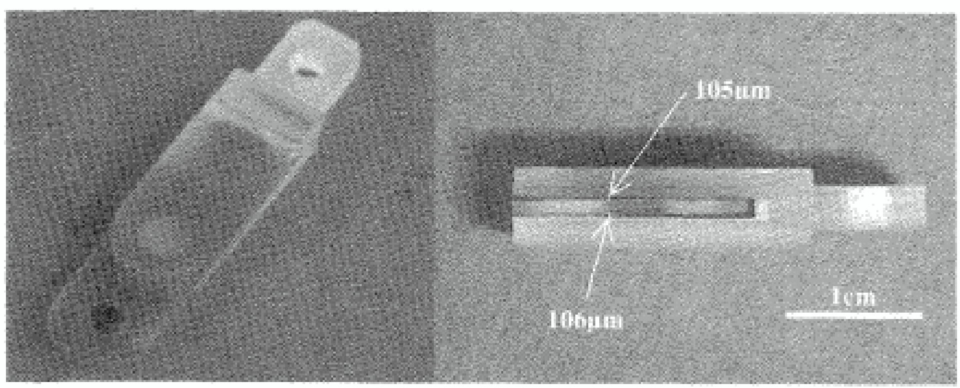


Figure 8: Fabricated object

CONCLUSIONS

1. Refrigerative stereolithography and a new method for masking the light from upper layers to restrain surplus growth and improve resolution in the height direction were proposed.
2. A prototype machine using the above methods was produced.
3. The effectiveness of the refrigerative stereolithography and the new masking method were confirmed by fabrication experiments.

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